

A multi-flow model for microquasars

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Abstract

We present a new picture for the central regions of Black Hole X-ray Binaries. In our view, these central regions have a multi-flow configuration which consists in (1) an outer standard accretion disc down to a transition radius r_J , (2) an inner magnetized accretion disc below r_J driving (3) a non relativistic self-collimated electron-proton jet surrounding, when adequate conditions for pair creation are met, (4) a ultra relativistic electron-positron beam.

This accretion-ejection paradigm provides a simple explanation to the canonical spectral states, from radio to X/ γ -rays, by varying the transition radius r_J and disc accretion rate \dot{m} independently. Large values of r_J and low \dot{m} correspond to Quiescent and Hard states. These states are characterized by the presence of a steady electron-proton MHD jet emitted by the disc below r_J . The hard X-ray component is expect to form at the jet basis. When r_J becomes smaller than the marginally stable orbit r_i , the whole disc resembles a standard accretion disc with no jet, characteristic of the Soft state. Intermediate states correspond to situations where $r_J \gtrsim r_i$. At large \dot{m} , an unsteady pair cascade process is triggered within the jet axis, giving birth to flares and ejection of relativistic pair blobs. This would correspond to the luminous intermediate state, sometimes referred to as the Very High state, with its associated superluminal motions. Some features such as possible hysteresis and the presence of quasi-periodic oscillations could be also described in this paradigm.

1. A novel framework for BH XrBs

1.1. General picture

We assume that the central regions of BH XrBs are composed of four distinct flows: two discs, one outer “standard” accretion disc (hereafter SAD) and one inner jet emitting disc (hereafter JED), and two jets, a non-relativistic, self-confined electron-proton MHD jet and, when adequate conditions for pair creation are met, a ultra-relativistic electron-positron beam. A sketch of our model is shown in Fig. 1 while the four dynamical components are discussed separately below. This is an extended version of the “two-flow” model early proposed for AGN and quasars (Pelletier et al., 1988; Sol et al., 1989; Pelletier & Roland, 1989; Henri & Pelletier, 1991; Pelletier & Sol, 1992) to explain the highly relativistic phenomena such as superluminal motions observed in these sources. This model provides a promising framework to explain the canonical spectral states of BH XrBs mainly by varying the transition radius r_J between the SAD and the JED. This statement is not new and has already been proposed in the past by different authors (e.g. Esin et al. 1997; Belloni et al. 1997; Livio et al. 2003; King et al. 2004) but our model distinguishes itself from the others by the consistency of its disc-jet structure and by the introduction of a new physical component, the ultra-relativistic electron-positron beam, that appears during strong outbursts.

We believe that jets from BH XrBs are self-collimated because they follow the same accretion-ejection correlation as in AGN (Corbel et al., 2003; Fender et al., 2003; Merloni et al., 2003). This therefore implies the presence of a large scale vertical field anchored

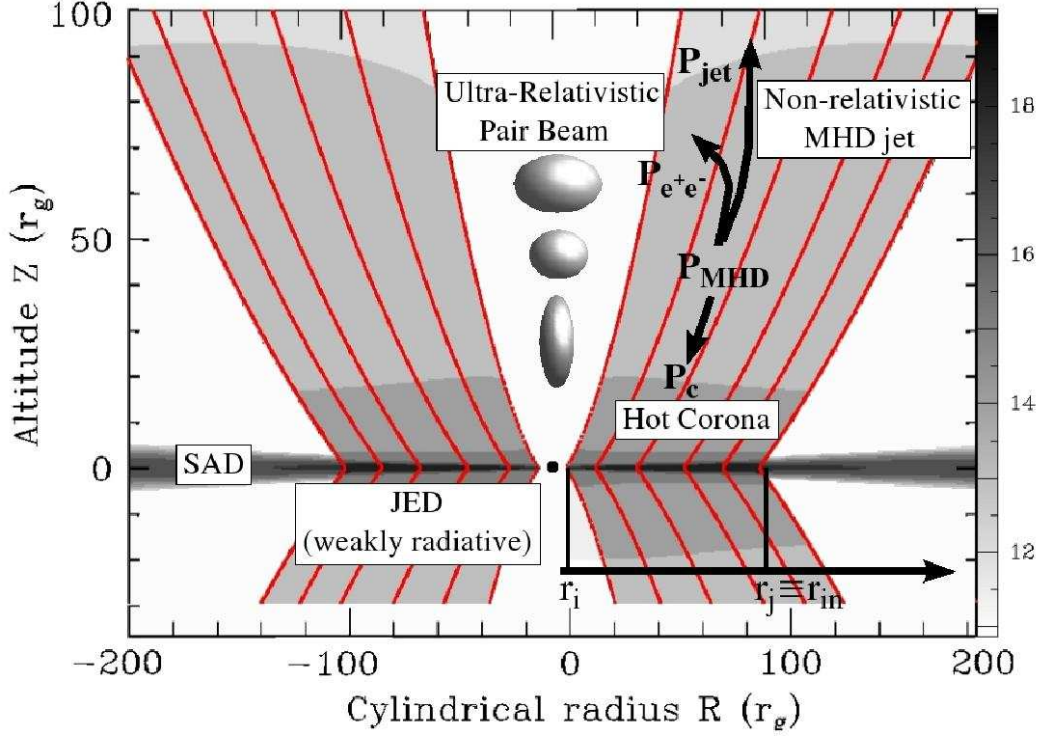


Fig. 1. A Standard Accretion Disc (SAD) is established down to a radius r_J which marks the transition towards a low radiative Jet Emitting Disc (JED), settled down to the last stable orbit. The JED is driving a mildly relativistic, self-collimated electron-proton jet which, when suitable conditions are met, is confining an inner ultra-relativistic electron-positron beam. The MHD power P_{MHD} flowing from the JED acts as a reservoir for (1) heating the jet basis (radiating as a moving thermal corona with power P_c), (2) heating the inner pair beam ($P_{e^+e^-}$) and (3) driving the compact jet (P_{jet}). Field lines are drawn in black solid lines and the number density is shown in greyscale ($\log_{10} n/\text{m}^{-3}$). This magnetic accretion-ejection structure solution was computed with $\xi = 0.01$, $\varepsilon = 0.01$ and with $m = 10$ and $\dot{m}(r_J) = 0.01$ (see text).

somewhere in the accretion disc (the JED) and we assume that this large scale B_z has the same polarity. The presence of a large scale vertical field threading the disc is however not sufficient to drive super-Alfvénic jets. This field must be close to equipartition as shown by Ferreira & Pelletier (1995) and Ferreira (1997). The reason is twofold. On one hand, the magnetic field is vertically pinching the accretion disc so that a (quasi) vertical equilibrium is obtained only thanks to the gas and radiation pressure support. As a consequence, the field cannot be too strong. But on the other hand, the field must be strong enough to accelerate efficiently the plasma right at the disc surface (so that the slow-magnetosonic point is crossed

smoothly). These two constraints can only be met with fields close to equipartition.

An important local parameter is therefore the disc magnetization $\mu = B_z^2/(\mu_o P_{tot})$ where P_{tot} includes the plasma and radiation pressures. In our picture, a SAD is established down to a radius r_J where μ becomes of order unity. Inside this radius, a JED with $\mu \sim 1$ is settled. At any given time, the exact value of r_J depends on highly non-linear processes such as the interplay between the amount of new large scale magnetic field carried in by the accreting plasma (eg. coming from the secondary) and turbulent magnetic diffusivity redistributing the magnetic flux already present. These processes are far to

be understood. For the sake of simplicity, we will treat in the following r_J as a free parameter that may vary with time (see Section 3).

1.2. The outer SAD

Accretion requires the presence of a negative torque extracting angular momentum. In a SAD this torque is assumed to be of turbulent origin and provides an outward transport of angular momentum in the radial direction. It has been modeled as an "anomalous" viscous torque of amplitude $\sim -\alpha_v P_{tot}/r$, where α_v is a small parameter (Shakura & Sunyaev, 1973). The origin of this turbulence is now commonly believed to arise from the magneto-rotational instability or MRI (Balbus & Hawley, 1991). The MRI requires the presence of a weak magnetic field ($\mu < 1$) and is quenched when the field is close to equipartition. We make the conjecture that a SAD no longer exists once μ reaches unity. Indeed, it can be easily shown that one may reasonably expect μ to increase towards the center (Ferreira et al., 2005). Whenever a BH XrB reaches $\mu \simeq 1$ at a radius $r_J > r_i$, r_i being the last marginally stable orbit, the accretion flow changes its nature to a JED. To summarize, the accretion flow at $r > r_J$ is a SAD with $\mu \ll 1$ fueled by the companion's mass flux and driving no outflow (constant accretion rate \dot{M}_a).

1.3. The inner JED

This inner region with $\mu \sim 1$ is fueled by the SAD at a rate $\dot{M}_{a,J} = \dot{M}_a(r_J)$. Since it undergoes mass loss, we parametrize the JED accretion rate following:

$$\dot{M}_a(r) = \dot{M}_{a,J} \left(\frac{r}{r_J} \right)^\xi \quad (1)$$

where ξ measures the local ejection efficiency (Ferreira & Pelletier, 1993). The global energy budget in the JED is $P_{acc,JED} = 2P_{rad,JED} + 2P_{MHD}$ where P_{MHD} is the MHD Poynting flux feeding a jet, whereas the liberated accretion power writes

$$P_{acc,JED} \simeq \frac{GM\dot{M}_{a,J}}{2r_i} \left[\left(\frac{r_i}{r_J} \right)^\xi - \frac{r_i}{r_J} \right] \quad (2)$$

The dynamical properties of a JED have been extensively studied in a series of papers (see Ferreira 2002 and references therein). The ra-

tio at the disc midplane of the jet torque to the turbulent "viscous" torque is

$$\Lambda \sim \frac{B_\phi^+ B_z / \mu_o h}{\alpha_v P_{tot} / r} \sim \frac{B_\phi^+ B_z}{\mu_o P_{tot}} \frac{r}{\alpha_v h} \quad (3)$$

It is straightforward to see that the necessary condition to drive jets (fields close to equipartition) from Keplerian discs leads to a dominant jet torque. In fact, it has been shown that steady-state ejection requires $\Lambda \sim r/h \gg 1$ (Ferreira, 1997; Casse & Ferreira, 2000a).

This dynamical property has a tremendous implication on the JED emissivity since it can be shown that the total luminosity $2P_{rad,JED}$ of the JED is only a fraction $1/(1 + \Lambda)$ of the accretion disc liberated power $P_{acc,JED}$ (Ferreira et al., 2005). In consequence, the JED is weakly dissipative while powerful jets are being produced regardless of the nature of the central object. As a consequence, the flux emitted by the JED is expected to be unobservable with respect to that of the outer SAD. Thus, the values of the "disc inner radius" (r_{in}) and "disc accretion rate" observationally determined from spectral fits must be understood here as values at the transition radius, namely $r_{in} \equiv r_J$ and $\dot{m} \equiv \dot{m}(r_J)$: the optically thick JED is spectrally hardly visible.

1.4. Non-relativistic electron-proton jets from JEDs

The ejection to accretion rate ratio in a JED writes $2\dot{M}_{jet}/\dot{M}_{a,J} \simeq \xi \ln(r_J/r_i)$. In principle, the ejection efficiency ξ can be observationally deduced from the terminal jet speed. Indeed, the maximum velocity reachable along a magnetic surface anchored on a radius r_o (between r_i and r_J) is $u_\infty \simeq \xi^{-1/2} \sqrt{GM/r_o}$ in the non-relativistic limit (see Ferreira 1997 for relativistic estimates). Although a large power is provided to the ejected mass (mainly electrons and protons), the mass loss (ξ) is never low enough to allow for speeds significantly relativistic required by superluminal motions: MHD jets from accretion discs are basically non or only mildly relativistic with $u_\infty \sim 0.1 - 0.8 c$ (Ferreira, 1997). This is basically the reason why they can be efficiently self-confined by the magnetic hoop stress. Indeed, in relativistic flows the electric field grows so much that it counteracts the confining effect due to the toroidal field. This dramatically reduces the self-collimation property of jets (Bogovalov & Tsinganos, 2001; Bogovalov,

2001; Pelletier, 2004).

In our framework, jets from magnetic accretion-ejection structure (hereafter MAES) have two distinct spectral components detailed below:

1.4.1. A non-thermal extended jet emission

We expect a small fraction of the jet power P_{jet} to be converted into particles, through first and/or second order Fermi acceleration, populating the MHD jet with supra-thermal particles. These particles are responsible for the bulk emission of the MHD jet. This is similar to models of jet emission already proposed in the literature (Falcke & Biermann, 1995; Vadawale et al., 2001; Markoff et al., 2001, 2003; Markoff, 2004; Falcke et al., 2004). In these models, the jet is assumed to be radiating self-absorbed synchrotron emission in the radio band (producing a flat or even inverted radio spectrum) becoming then optically thin in the IR-Optical bands and providing a contribution up to the X/ γ -rays.

1.4.2. A thermal jet basis

Jet production relies on a large scale magnetic field anchored on the disc as much as on MHD turbulence triggered (and sustained) within it. This implies that small scale magnetic fields are sheared by the disc differential rotation, leading to violent release of magnetic energy at the disc surface and related turbulent heat fluxes (e.g. Galeev et al. 1979; Heyvaerts & Priest 1989; Stone et al. 1996; Merloni & Fabian 2002). The energy released is actually tapping the MHD Poynting flux flowing from the disc surface. We can safely assume that a fraction f of it would be deposited at the jet basis, with a total power $P_c = fP_{MHD}$. The dominant cooling term in this optically thin medium is probably comptonization of soft photons emitted by the outer SAD (with a small contribution from the underlying JED). These are circumstances allowing a thermal plasma to reach a temperature as high as ~ 100 keV, (Pietrini & Krolik, 1995; Mahadevan, 1997; Esin et al., 1997). This plasma being at the base of the jet, it will have a vertical proper motion. Then its spectral behavior is expected to be close to that of a dynamic corona (Malzac et al., 2001).

1.5. The inner ultra-relativistic pair beam

Since the large scale magnetic field driving the self-confined jet is anchored onto the accretion disc which has a non zero inner radius, there is a natural hole on the axis above the central object with no baryonic outflow (this also holds for neutron stars). This hole provides a place for pair production and acceleration with the outer MHD jet acting as a sheath that confines and heats the pair plasma. This is the microquasar version of the "two flow" model that has been successfully applied to the high energy emission of relativistic jets in AGNs (Henri & Pelletier, 1991; Marcowith et al., 1995, 1998; Renaud & Henri, 1998).

The $e^+ - e^-$ plasma is produced by $\gamma - \gamma$ interaction, the γ -ray photons being initially produced by a few relativistic particles by Inverse Compton process, either on synchrotron photons (Synchrotron Self Compton or SSC) or on disc photons (External Inverse Compton or EIC).

It is well known that above 0.5 MeV photons can annihilate with themselves to produce an electron-positron pair. Usually, pairs are assumed to cool once they are formed, producing at turn non thermal radiation. Some of this radiation can be absorbed to produce new pairs, but the overall pair yield never exceeds 10 %. A key point of the two-flow model however is that the MHD jet launched from the disc can carry a fair amount of turbulent energy, most probably through its MHD turbulent waves spectrum. A fraction of this power can be transferred to the pairs ($P_{e^+e^-} \ll P_{MHD}$). Thus the freshly created pairs can be continuously reheated, triggering an efficient pair runaway process, leading to a dense pair plasma (Henri & Pelletier, 1991).

As we said, reacceleration is balanced by cooling through the combination of synchrotron, SSC and EIC processes. Synchrotron and SSC emission are quasi isotropic in the pair frame, but the external photon field is strongly anisotropic. The pair plasma will then experience a strong bulk acceleration due to the recoil term of EIC, an effect also known as the "Compton Rocket" effect (O'Dell, 1981; Renaud & Henri, 1998). As shown in previous works, this "rocket" effect is the key process to explain relativistic motion (Marcowith et al., 1995; Renaud & Henri, 1998). For example, values of 5 to 10 can be easily reached in near-Eddington accretion regime around stellar

black holes (Renaud & Henri, 1998).

Producing this pair plasma requires thus altogether a strong MHD jet, a radiative non-thermal component extending above the MeV range and a minimal γ – γ optical depth, namely $\tau_{\gamma\gamma} \sim 1$. Using simple estimates, the optical depth $\tau_{\gamma\gamma}$ for absorbing photons with energy $E_\gamma = \varepsilon m_e c^2$ is approximately, for a spherical source of radius R filled by soft photons with a power-law distribution $\nu L_\nu = EL_E = L_0(E/E_0)^{-\Gamma+2}$ (where Γ is the soft photon index):

$$\tau_{\gamma\gamma}(E_\gamma) = 0.7 \times 262^{(2.5-\Gamma)} \left(\frac{L_0}{0.1 L_{Edd}} \right) \times \left(\frac{R}{30 r_g} \right)^{-1} \left(\frac{E_0}{1 \text{ keV}} \right)^{\Gamma-2} \left(\frac{E_\gamma}{1 \text{ MeV}} \right)^{\Gamma-1} \quad (4)$$

where $r_g = GM/c^2$. Thus, good conditions for pair creation require high luminosity, small size and high energy ($> \text{MeV}$) photons.

It is noteworthy that the pair beam is intrinsically highly variable and subject to an intermittent behavior. Indeed, once the pair creation is triggered, a regulation mechanism must occur to avoid infinite power of the pair plasma and limit the pair run-away. This is probably realized by the quenching of the turbulence ($P_{e^+e^-}$ vanishes) when most of its energy is suddenly tapped by the catastrophic number of newly created pairs. These pairs will therefore simply expand freely, confined by the heavier MHD jet. One would then expect a flare in the compact region, followed by the ejection of a superluminal radio component, analogous to those observed in AGNs (Saugé & Henri 2005, A&A submitted). Such a situation can repeat itself as long as the required physical conditions are met. Alternatively, it may also be that the formation of a dense pair beam destroys the surrounding MHD jet, explaining the disappearance of the compact jet after a strong ejection event.

2. Canonical spectral states of X-ray binaries

2.1. The crucial roles of r_J and \dot{m}

From Section 1, it is clear that the spectral appearance of a BH XrB critically depends on the size of the JED relative to the SAD, namely r_J . As stated before, r_J is the radius where the disc magnetization $\mu = B_z^2/(\mu_0 P_{tot})$ becomes of order unity. Thus, r_J depends on two quantities

$P_{tot}(r, t)$ and $B_z(r, t)$. The total pressure is directly proportional to \dot{m} since $P_{tot} = \rho \Omega_k^2 h^2 \propto \dot{m} m^{-1} r^{-5/2}$. As a consequence, any variation of the accretion rate in the outer SAD implies also a change in the amplitude of the total pressure. But we have to assume something about the time evolution of the large scale magnetic field threading the disc. The processes governing the amplitude and time scales of these adjustments of r_J to a change in \dot{m} are far too complex to be addressed here. They depend on the nature of the magnetic diffusivity within the disc but also on the radial distribution of the vertical magnetic field. We will simply assume in the following that r_J and \dot{m} are two independent parameters. In that respect, our view is very different from that of Esin et al. (1997); Mahadevan (1997) who considered only the dependency of \dot{m} to explain the different spectral states of BH XrBs.

2.2. The Quiescent state

This state is characterized by a very low accretion rate (\dot{m} as low as $\sim 10^{-9}$) with a hard X-ray component. The ADAF model has been successfully applied to some systems with a large transition radius between the ADAF and the outer standard disc, namely $r_{tr} \sim 10^3 - 10^4 r_g$ (e.g. Narayan et al. 1996; Hameury et al. 1997). However, such a model does not account for jets and their radio emission, even though XrBs in quiescence seem also to follow the radio/X-ray correlation (e.g. Fender et al. 2003; Gallo et al. 2004, 2005).

Within our framework, a BH XrB in quiescence has a large r_J , so that a large zone in the whole disc is driving jets (Fig. 2a). The low \dot{m} provides a low synchrotron jet luminosity, while the JED is optically thin, producing a SED probably very similar to that of an ADAF. We thus expect $r_J \sim r_{tr}$. The weak MHD Poynting flux prevents the ignition of the pair cascade process and no pair beam is produced.

2.3. The Hard state

Within our framework, the JED is now more limited radially than in the Quiescent state, namely $r_J \sim 40 - 100 r_g$ (Fig. 2b). This transition radius corresponds to the inner disc radius r_{in} as obtained within the SAD framework (Zdziarski et al., 2004). The low velocity of the plasma expected at the jet basis is in good agreement with recent studies of XrBs in Hard state

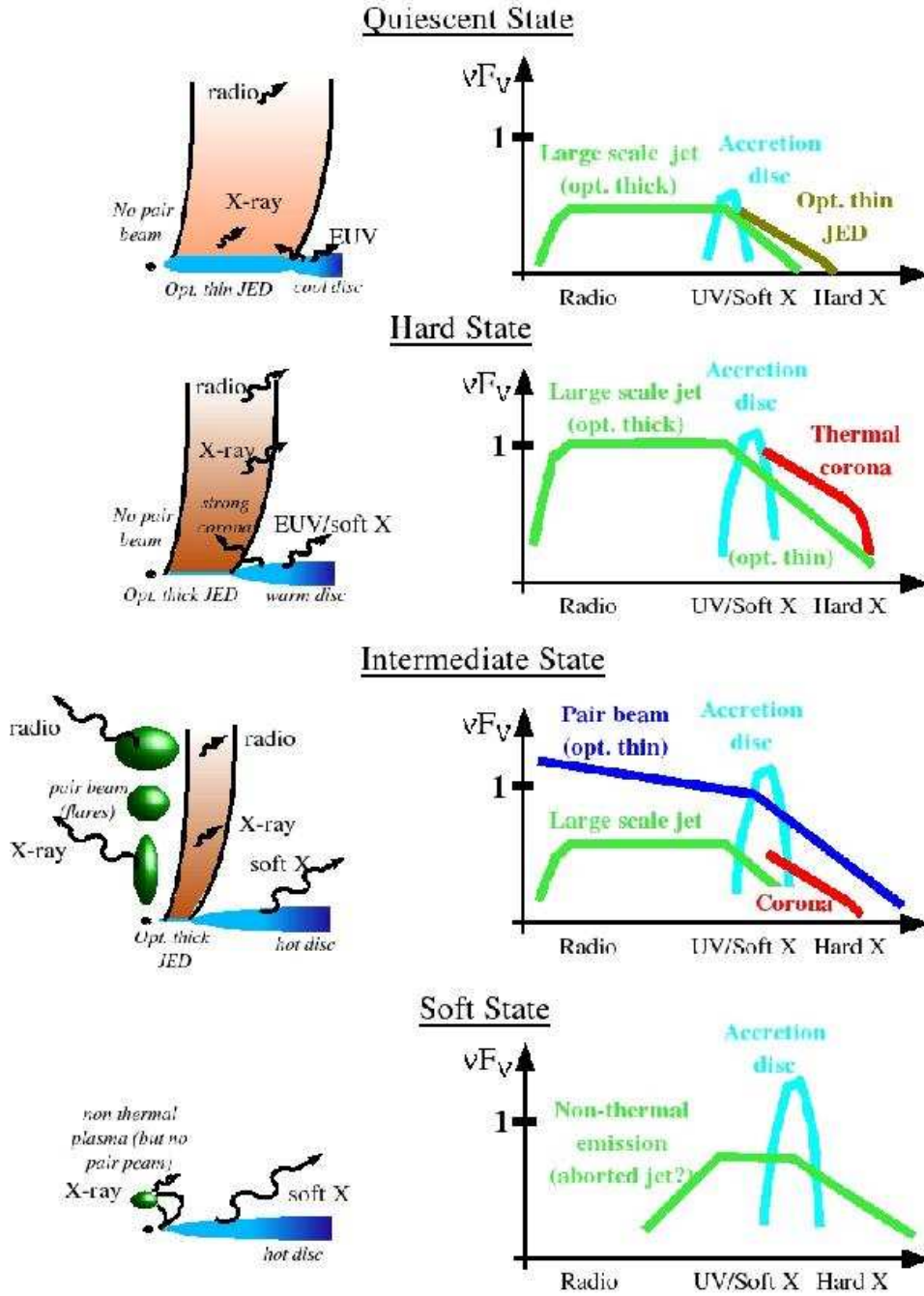


Fig. 2. The canonical spectral states of X-ray binaries (cf. Sect. 2 for more details). (a) Quiescent state obtained with a low \dot{m} and a large r_J : the Jet Emitting Disc (JED) occupies a large zone in the accretion disc. (b) Hard state with much larger \dot{m} and smaller r_J : the pair creation threshold is still not reached. (c) Luminous Intermediate state between the Hard and the Soft states: the high disc luminosity combined with the presence of a MHD jet allows pair creation and acceleration along the axis, giving birth to flares and superluminal ejection events. (d) Soft state when there is no zone anymore within the disc where an equipartition field is present: no JED, hence neither MHD jet nor pair beam.

(Maccarone, 2003; Gallo et al., 2003). It can also explain the apparent weakness of the Compton reflection (Zdziarski et al., 1999; Gilfanov et al., 1999) as already suggested by Markoff et al. (2003, see also Beloborodov 1999; Malzac et al. 2001) and tested by Markoff & Nowak (2004). In any case, the JED intrinsic emission is weak with respect to that of the outer standard disc: most of the accretion power flows out of the JED as an MHD Poynting flux. Nevertheless, the threshold for pair creation is still not reached and there is no pair beam, hence no superluminal motion. The MHD power is therefore shared between the jet basis, whose temperature increases (the thermal "corona") producing X-rays, and the large-scale jet seen as the persistent (synchrotron) radio emission.

2.4. The Soft state

Our interpretation of the Soft state relies on the disappearance of the JED, i.e. when r_J becomes smaller or equal to r_i (Fig. 2c). Depending on the importance of the magnetic flux in the disc, this may occur at different accretion rates. Thus, the threshold in \dot{m} where there is no region anymore in the disc with equipartition fields may vary. The whole disc adopts therefore a radial structure akin to the standard disc model. Since no MHD jet is produced, all associated spectral signatures disappear. Even if pair production may take place (when \dot{m} is large), the absence of the confining MHD jet forbids the pairs to get warm enough and be accelerated: no superluminal motion should be detected.

Note also that the presence of magnetic fields may be the cause of particle acceleration responsible for the weak hard-energy tail (McCR03, Zdziarski & Gierlinski 2003 and references therein).

2.5. Intermediate states

This state has been first identified at large luminosities ($L > 0.2 L_{Edd}$) and was initially called Very High state. However, high luminosity appeared to not be a generic feature since it has been observed at luminosities as low as $0.02 L_{Edd}$ (McCR03, Zdziarski & Gierlinski 2003). Therefore, the most prominent feature is that these states are generally observed during transitions between Hard and Soft states. Within our framework, they correspond to geometrical situations where r_J is small but remains larger than r_i (Fig. 2d). The

flux of the outer standard disc is thus still important while the JED is disappearing. The consequences on the spectral shape are not straightforward since the importance of the different spectral components relative to each other depends on the precise values of r_J and \dot{m} . Such study is out of the scope of the present paper and will be detailed elsewhere.

The crucial point however is that, in our framework, luminous intermediate states (the so-called Very High State or VHS) with high \dot{m} provide the best conditions for the formation of the ultra-relativistic pair beam, as described in details in Sect. 1.5: (1) a high luminosity, (2) a high energy steep power law spectrum extended up to the γ -ray bands and (3) the presence of the MHD jet. The two first characteristics enable a $\gamma - \gamma$ opacity larger than unity (cf. Eq. 4 of Sect. 1.5), while the MHD jet allows to confine the pair beam and maintain the pairs warm, a necessary condition to trigger a pair runaway process. The total emission would be then dominated by the explosive behavior of the pairs, with the sudden release of blobs. Each blob produced in the beam first radiates in X and γ -ray, explaining the hard tail present in this state, and then, after a rapid expansion, produces the optically thin radio emission. The production of a series of blobs can even result in an apparently continuous spectrum, from radio to X/ γ -rays. This pair beam would also explain the superluminal ejections observed during this state in different objects (e.g. Sobczak et al. 2000; Hannikainen et al. 2001). We conjecture that the exact moment where this occurs corresponds to the crossing of the "jet line" recently proposed by Fender et al. (2004b) (see also Corbel et al. 2004). This corresponds to a transition from the "hard" intermediate state to the "soft" one.

3. Time evolution of BH XrBs

The evolution with time of a BH XrB has been reported in Fig. 3 (Ferreira et al. in preparation). This is a synthetic Hardness-Intensity diagram (hereafter HID) as it is generally observed in XrBs in outbursts (e.g. Belloni et al. 2005; Fender et al. 2002, 2004). During such outbursts, the objects follow the A-B-C-D sequence before turning back to A at the end of the outburst. We detailed below the interpretation of this diagram in the framework of our model. We have also overplotted on Fig.

3 the different sketches of our model at different phases (this figure is clearly inspired by Fig. 7 of Fender et al. 2004).

3.1. Ascending the Right Branch:

Let us start at a Low/Hard State located at the bottom of the HID right branch (in A in Fig. 3). In our view, such state would correspond to a JED extending up to typically $r_J \sim 10^2 r_g$. This considerably lowers the emission from the inner radii of the SAD producing a UV/soft X-ray excess. The hard (1-20 keV) power-law component of photon index $\Gamma \sim 1.7$ is attributed to the warm thermal plasma at the base of the jet. The non relativistic MHD jet then produces the persistent IR and radio synchrotron emission.

3.2. The Top Horizontal Branch

Before the jet line: Arriving in B we assume that r_J starts decreasing rapidly. Then, the MAES undergoes an outside-in transition to a SAD. The BH XrBs enter the high intermediate state.

The flux of the outer standard disc then increases while the JED is decreasing. Under such circumstances, the MHD Poynting flux released by the JED is still important (through the large \dot{m} that characterizes this part of the HID) but the MHD jet itself fills a smaller volume, a direct consequence being a weaker emission of the thermal "corona" and the non-thermal MHD jet emission with respect to what it is while in the Hard state.

At the jet line: During its evolution along this top horizontal branch the system can reach a critical phase where the conditions for a strong pair production, inside the MHD jet structure, are fulfilled.

In this case, we expect an explosive behaviour of the pairs, with the sudden release of blobs. The emission of these blobs, first in X and γ -ray and then, after a rapid expansion, in IR and radio, will probably dominate the broad band spectrum, producing the hard X-ray tail and the optically thin radio emission present in this state. The production of a series of blobs can even result in an apparently continuous spectrum, from radio to X/ γ -rays.

Remarkably, there is no evidence of steady

radio jets during this phase but it is generally associated with radio and X-ray flares and/or superluminal sporadic ejections (e.g. Sobczak et al. 2000; Hannikainen et al. 2001).

We note that the rapid increase of the pair beam pressure in the inner region of the MHD jet, during e.g. a strong outburst, may dramatically perturb the MHD jet production. Indeed, a huge pair pressure at the axis may enforce the magnetic surfaces to open dramatically, thereby creating a magnetic compression on the disc (actually the JED) so that no more ejection is feasible. Alternatively, it is also possible that the racing of the pair process completely wears out the MHD Poynting flux released by the JED, suppressing the jet emission or even the jet itself. Whatever occurs (i.e. jet destruction or jet fading), we expect a suppression of the steady jet emission when a large outburst sets in. Interestingly, the detailed spectral and timing study of the radio/X-ray emission of four different black hole binaries during a major radio outburst (Fender et al., 2004b) shows a weakening and softening of the X-ray emission as well as a the quenching of the radio emission after the burst. This is in good agreement with our expectations since the cooling of the pair beam should indeed results in a flux decrease and a softening of its spectrum.

It is also worth noting that within our picture, we do not expect all BH XrBs to reach a "pair production" phase along the top branch. Indeed, it requires a rather high accretion rate so that the gamma-gamma opacity reaches unity in order to trigger the pair cascade process. Moreover, a large accretion rate implies a large disc pressure. Since the pair beam requires to be surrounded by a MHD jet (for confinement and energetic reasons), this also implies a large magnetic flux in the disc able to match this increase in P_{tot} . In practice, one needs to have $r_J \sim 10 r_g$ at these high levels of accretion activity (cf. Eq. 4).

After the jet line: We assume that r_J is still decreasing. We therefore expect the total disappearance of the JED and its MHD jets when $r_J \rightarrow r_i$, thereby also causing the end of the pair beam (if present). The inner regions of the BHB are a SAD with probably a magnetically active "corona". Indeed, it must be noted that the situation might be slightly more complex than a mere SAD because of the presence of a concentrated magnetic flux. No steady MHD

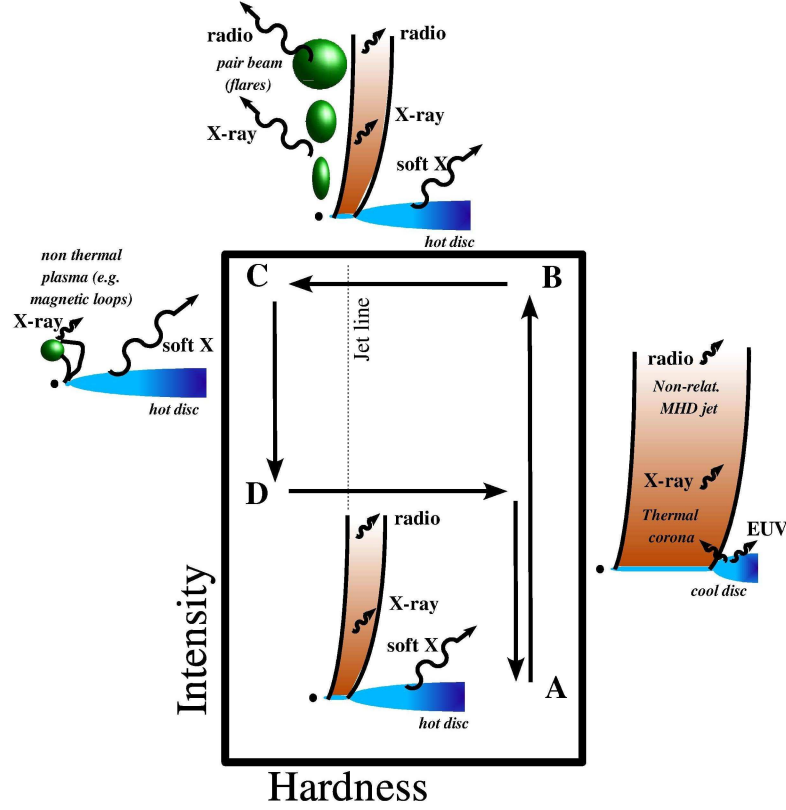


Fig. 3. Schematic Hardness–Intensity diagram as it is generally observed in XrBs in outbursts (this figure is clearly inspired by Fig. 7 of Fender et al. 2004). During such outbursts, the objects follow the A-B-C-D sequence before turning back to A at the end of the outburst. The interpretation of this diagram within our framework is detailed in Sect. 3.

ejection can be produced from the SAD but unsteady events could always be triggered. This is maybe the reason why this region in the HID seems to harbor complex variability phenomena (Belloni et al., 2005; Nespoli et al., 2003).

We note also that we still expect the presence of magnetic fields that may be the cause of particle acceleration responsible for the weak hard-energy tail generally observed in this state (McCR03, ZG04 and references therein).

3.3. Descending the Left Branch

When XrBs reach the left vertical branch (point C in Fig. 3), r_J is smaller than the inner disc radius i.e. the JED and the MHD jet have completely disappeared. The whole disc adopts therefore a radial structure akin to the standard disc model and we enter into the so-called soft state (also called thermal dominant state McCR03) where the spectra are dominated by strong disc emission. The descent from C to D correspond to a decrease in intensity i.e. by a decrease of the accretion rate. This is the beginning of the fading phase of the outburst. In our framework r_J keeps smaller than r_i .

3.4. The Low Horizontal Branch

In D r_J begins to increase again. Thus, according to this conjecture, there is an inside-out build up of a JED. Self-collimated electron-proton jets could be produced right away. This means an increase of r_j , the reappearance of the non-thermal MHD jet and the thermal corona at its basis and a decrease of the SAD emission. But, contrary to the Top Horizontal Branch, the accretion rate is now too low to allow the production of a pair beam. Consequently we do not expect superluminal motions during this phase.

3.5. The Quiescent State

When r_J reaches the same value as in the Low/Hard State the system is ready for another duty cycle. But much larger values of r_J can be obtained, following the same process, if the accretion rate undergoes a strong decline towards quiescent levels.

In our picture, the Quiescent State should be described by a large radial extension covered by an underluminous JED with $\mu \sim 1$. A large zone in the whole disc is therefore driving jets as inferred from some observations (e.g. Fender et al. 2003; Gallo et al. 2004). Jets are radiating through synchrotron emission and produce an optically thick radio spectrum (although very low). On the other hand, for such a low accretion rate, the JED is expected to be in large part optically thin. The computation of the SEDs have been undergone (Petrucchi et al. in preparation).

4. Summary and concluding remarks

We present in this paper a new paradigm for the accretion-ejection properties of Galactic Black Hole X-ray binaries. We assume the existence of a large scale magnetic field of bipolar topology in the innermost disc regions. Such a field allows for several dynamical phenomena to occur whose relative importance determine the observed spectral state of the binary. The dynamical constituents are: (1) an outer standard accretion disc (SAD) for $r > r_J$, (2) an inner Jet Emitting Disc (JED) for $r < r_J$ driving (3) a self-collimated non-relativistic electron-proton surrounding, when adequate conditions are met, (4) a ultra-relativistic electron-positron beam. The dynamical properties of each constituent have been thoroughly analyzed in previous works (e.g. Shakura & Sunyaev 1973; Henri & Pelletier 1991; Ferreira & Pelletier 1995; Marcowith et al. 1997; Renaud & Henri 1998; Saugé & Henri 2003, 2004), but it is the first time where they are invoked altogether as necessary ingredients to reproduce the different spectral states of a same object.

We showed that the various canonical states can be qualitatively explained by varying *independently* the transition radius r_J and the disc accretion rate \dot{m} . In our view, the Quiescent and Hard states are dominated by non relativistic jet production from the JED, providing henceforth a persistent synchrotron jet emission. The Soft state is obtained when the transition radius r_J becomes smaller than the last marginally

stable orbit r_i , a SAD is established throughout the whole accretion disc. Intermediate states, between Hard and Soft, are expected to display quite intricate and variable spectral energy distributions. Luminous Intermediate states, obtained during the Hard-to-Soft transitions, are those providing the unique conditions for intermittent pair creation. These pairs give rise to a ultra relativistic beam propagating on the MHD jet axis, explaining both the observed superluminal motions and hard energy tail.

The dynamical structure presented here (JED, SAD, MHD jet and, occasionally, a pair beam) seems to be consistent with all available information about the canonical spectral states of BH XrBs. However, a more quantitative analysis is critical. In particular, we need to show that the base of the MHD jet can indeed provide a hot corona with the correct spectral signature. Then, a precise estimate of the radio/X-ray correlation predicted by our model and its comparison to observations (through the computation of SEDs) will be a test of prime importance for its validity (Petrucchi et al., in preparation).

In our view, the magnetic flux available at the inner disc regions is a fundamental and unavoidable ingredient that most probably varies from one system to another. We believed that it controls, with \dot{m} , the evolution of the transition radius r_J , through the variation of the magnetization μ in the different part of the accretion disc. The variation of μ and \dot{m} all along the HID diagram would explain the variation of r_J . This is a work in progress (Ferreira et al. in preparation).

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References

- Ballbus, S. A. & Hawley, J. F. 1991, ApJ, 376, 214
- Belloni, T., Homan, J., P., C., et al. 2005, astro-ph/0504577
- Belloni, T., Mendez, M., King, A. R., van der Klis, M., & van Paradijs, J. 1997, ApJ, 479, L145+
- Beloborodov, A. M. 1999, in ASP Conf. Ser. 161: High Energy Processes in Accreting Black Holes, 295–+

- Bogovalov, S. & Tsinganos, K. 2001, MNRAS, 325, 249
- Bogovalov, S. V. 2001, A&A, 371, 1155
- Bosch-Ramon, V. & Paredes, J. M. 2004a, A&A, 417, 1075
- Bosch-Ramon, V. & Paredes, J. M. 2004b, A&A, 425, 1069
- Casse, F. & Ferreira, J. 2000a, A&A, 353, 1115
- Casse, F. & Ferreira, J. 2000b, A&A, 361, 1178
- Corbel, S., Fender, R. P., Tomsick, J. A., Tzioumis, A. K., & Tingay, S. 2004, ApJ, 617, 1272
- Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, A&A, 400, 1007
- Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
- Falcke, H. & Biermann, P. L. 1995, A&A, 293, 665
- Falcke, H., Körding, E., & Markoff, S. 2004, A&A, 414, 895
- Fender, R., Wu, K., Johnston, H., et al. 2004a, Nature, 427, 222
- Fender, R. P., Belloni, T. M., & Gallo, E. 2004b, MNRAS, 355, 1105
- Fender, R. P., Gallo, E., & Jonker, P. G. 2003, MNRAS, 343, L99
- Ferreira, J. 1997, A&A, 319, 340
- Ferreira, J. 2002, in "Star Formation and the Physics of Young Stars", J. Bouvier and J.-P. Zahn (Eds), EAS Publications Series, astro-ph/0311621, 3, 229
- Ferreira, J. & Casse, F. 2004, ApJ, 601, L139
- Ferreira, J. & Pelletier, G. 1993, A&A, 276, 625+
- Ferreira, J. & Pelletier, G. 1995, A&A, 295, 807+
- Ferreira, J., Petrucci, P. O., Henri, G., Saugé, L., & Pelletier, G. 2005, A&A
- Frontera, F., Palazzi, E., Zdziarski, A. A., et al. 2001, ApJ, 546, 1027
- Galeev, A. A., Rosner, R., & Vaiana, G. S. 1979, ApJ, 229, 318
- Gallo, E., Corbel, S., Fender, R. P., Maccarone, T. J., & Tzioumis, A. K. 2004, MNRAS, 347, L52
- Gallo, E., Fender, R. P., & Hynes, R. I. 2005, MNRAS, 356, 1017
- Gallo, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60
- Gilfanov, M., Churazov, E., & Revnivtsev, M. 1999, A&A, 352, 182
- Giozzi, M., Bodo, G., & Ghisellini, G. 1999, MNRAS, 303, L37
- Gnedin, Y. N., Borisov, N., Natsvlshvili, T., Piotrovich, M., & Silant'ev, N. 2003, in Gnedin, Y. N. & Natsvlshvili, T. M. 1997, in Stellar Magnetic Fields, Proceedings of the International Conference, held in the Special Astrophysical Observatory of the Russian AS, May 13-18, 1996, Eds.: Yu. Glagolevskij, I. Romanyuk, Special Astrophysical Observatory Press, p. 40-54., 40-54
- Haardt, F. 1993, ApJ, 413, 680
- Hameury, J.-M., Lasota, J.-P., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 234
- Hannikainen, D., Campbell-Wilson, D., Hunstead, R., et al. 2001, Astrophysics and Space Science Supplement, 276, 45
- Henri, G. & Pelletier, G. 1991, ApJ, 383, L7
- Heyvaerts, J. F. & Priest, E. R. 1989, A&A, 216, 230
- King, A. R., Pringle, J. E., West, R. G., & Livio, M. 2004, MNRAS, 348, 111
- Lasota, J.-P., Narayan, R., & Yi, I. 1996, A&A, 314, 813
- Livio, M., Pringle, J. E., & King, A. R. 2003, ApJ, 593, 184
- Maccarone, T. J. 2003, A&A, 409, 697
- Mahadevan, R. 1997, ApJ, 477, 585
- Malzac, J., Beloborodov, A. M., & Poutanen, J. 2001, MNRAS, 326, 417
- Marcowith, A., Henri, G., & Pelletier, G. 1995, MNRAS, 277, 681
- Marcowith, A., Henri, G., & Renaud, N. 1998, A&A, 331, L57
- Marcowith, A., Pelletier, G., & Henri, G. 1997, A&A, 323, 271
- Markoff, S. 2004, in X-ray Binaries to Quasars: Black Hole Accretion on All Mass Scales, ed. T. J. Maccarone, R. P. Fender, and L. C. Ho
- Markoff, S., Falcke, H., & Fender, R. 2001, A&A, 372, L25
- Markoff, S., Nowak, M., Corbel, S., Fender, R., & Falcke, H. 2003, A&A, 397, 645
- Markoff, S. & Nowak, M. A. 2004, ApJ, 609, 972
- Massi, J. M., M., R., J.M., P., et al. 2004, in AIP Proceedings Series astro-ph/0410504
- Merloni, A. & Fabian, A. C. 2002, MNRAS, 332, 165
- Merloni, A., Heinz, S., & di Matteo, T. 2003, MNRAS, 345, 1057
- Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821
- Nespoli, E., Belloni, T., Homan, J., et al. 2003, A&A, 412, 235
- Nowak, M. A., Wilms, J., & Dove, J. B. 2002, MNRAS, 332, 856
- O'Dell, S. L. 1981, ApJ, 243, L147
- Paredes, J. M. 2004, in V Microquasar Workshop, Beijing, June 2004

- astro-ph/0409226
- Paredes, J. M., Martí, J., Ribó, M., & Massi, M. 2000, *Science*, 288, 2340
- Pelletier, G. 2004, in *Dynamics and dissipation in electromagnetically dominated media* (Nova Science) edited by M. Lyutikov (astro-ph/0405113)
- Pelletier, G. & Roland, J. 1989, *A&A*, 224, 24
- Pelletier, G. & Sol, H. 1992, *MNRAS*, 254, 635
- Pelletier, G., Sol, H., & Asseo, E. 1988, *Phys. Rev. A*, 38, 2552
- Pietrini, P. & Krolik, J. H. 1995, *ApJ*, 447, 526
- Poutanen, J. & Svensson, R. 1996, *ApJ*, 470, 249
- Renaud, N. & Henri, G. 1998, *MNRAS*, 300, 1047
- Saugé, L. & Henri, G. 2003, *New Astronomy Review*, 47, 529
- Saugé, L. & Henri, G. 2004, *ApJ*, 616, 136
- Shakura, N. I. & Sunyaev, R. A. 1973, *A&A*, 24, 337
- Sidoli, L. & Mereghetti, S. 2002, *A&A*, 388, 293
- Sobczak, G. J., McClintock, J. E., Remillard, R. A., et al. 2000, *ApJ*, 544, 993
- Sol, H., Pelletier, G., & Asseo, E. 1989, *MNRAS*, 237, 411
- Stone, J. M., Hawley, J. F., Gammie, C. F., & Balbus, S. A. 1996, *ApJ*, 463, 656
- Tagger, M., Varnière, P., Rodriguez, J., & Pellat, R. 2004, *ApJ*, 607, 410
- Vadawale, S. V., Rao, A. R., & Chakrabarti, S. K. 2001, *A&A*, 372, 793
- Zdziarski, A. A., Gierliński, M., Mikołajewska, J., et al. 2004, *MNRAS*, 351, 791
- Zdziarski, A. A. & Gierlinski, M. 2003, in *Proceedings of "Stellar-mass, intermediate-mass, and supermassive black holes"*, Kyoto astro-ph/0403683 (ZG04), 99–119
- Zdziarski, A. A., Lubinski, P., & Smith, D. A. 1999, *MNRAS*, 303, L11